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Sutural Effects of Fronto-Occipital Cranial Modification

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ABSTRACT Maya adult crania from the site of Lamanai, Belize provide a retrospective means of examining growth processes in the cranial vault. The Lamanai population practiced fronto-occipital deformation which is found to be significantly associated with premature sagittal synostosis and wormian bones of the lambdoidal suture. The undeformed members of the population also exhibit an abnormally high frequency of sagittal synostosis, but a significantly lower frequency than the deformed sample. It is suggested that the deforming apparatus creates tensile forces on the sagittal suture during the peak period of growth of the parietals, and that these forces might induce an adaptive response important in producing premature sagittal synostosis. The undeformed sample may have an increased congenital risk of sagittal synostosis created by their natural brachycephalic morphology in utero. The frequency patterning of wormian bones suggests a mixture of genetic and environmental causes in which tensile forces may also play a role.

Cranial modification represents a natural experiment which allows us to understand cranial growth processes and interrelationships between the cranial vault, base, and face (Anton, 1989; Cheverud et al., 1992; Kohn et al., 1993), and therefore, may ultimately help us to explain evolutionary processes. The research presented here aids the understanding of growth processes and functional relationships as they involve the effects of cranial deformation on sutural development and growth. It investigates the occurrence of premature sagittal synostosis and sutural bones in the Maya from Lamanai, Belize.

The practice of purposefully altering the natural morphology of the cranial vault has a wide geographical and temporal distribution (Lunier, 1869; Magitot, 1885; Dorsey, 1895; Hrdlicka, 1905, 1922; McGibbon, 1912; Boaz, 1913; Stokes, 1920; Dingwall, 1931; Goldstein, 1940; Newman, 1942; Hasluck, 1947; Field, 1948; Imbelloni, 1950; Briggs, 1952; Blackwood and Danby, 1955; Brothwell, 1963; Roger, 1975; Munizaga, 1976; Gerszten, 1993). For many physical anthropologists in the early part of this century, research goals pertaining to cranial deformation often mirrored those of contemporary archaeological research, e.g., description, typology, and mapping geographical distributions. Nonetheless, some of the earliest investigations into the relationship between function, growth, and morphology also emerged at this time (Oetteking, 1924, 1930). Such functionally based work foreshadowed that of medical doctors, dentists, and orthodontists, for whom an understanding of cranial morphogenesis under mechanical stress has been critical in clinical treatment (Moss, 1955, 1958; Young, 1957, 1959; Moss and Young, 1960; Björk and Björk, 1964; McNeill and Newton, 1965). These studies have also influenced and informed current anthropological research.

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SAGITTAL SYNOSTOSIS

In modern populations, sagittal synostosis is the most common of craniostenoses, or premature fusion of cranial sutures, representing 60–78% of cases (Ingraham and Matson, 1954; Knudson and Flaherty, 1960; Cohen, 1986). It normally occurs in approximately 0.4 per 1,000 live births (Graham et al., 1979; Cohen, 1986), and about three times (3.3:1) more frequently in males than in females (Di Rocco and Velardi, 1984). Sagittal synostosis characteristically results in a long, narrow (dolichocephalic), keel-shaped (scaphocephalic) vault (Hemple et al., 1961) as normal growth vectors are altered. Craniostenosis is "pathogenetically heterogeneous" (Cohen, 1986). In addition to genetic, metabolic, and teratogenic associations, sagittal synostosis occurs as part of several congenital syndromes (e.g., Apert's and Crouzon's Syndromes), and has often been associated with deformation of the cranial base.

Two dominant theories of causation specifically involve the relationship between the cranial base and the fused suture. Virchow (1851) thought that sagittal suture fusion caused cranial base deformity, while Moss (1959, 1975) believed that cranial base deformity caused sagittal sutural fusion. This issue is far from resolution, as some research suggests that premature sagittal synostosis does not result from cranial base deformity (Kreiborg, 1986; Marsh and Vannier, 1986; Kohn et al., 1994), while other research suggests that it does (Bennett, 1967; Tessier, 1971; Burdi et al., 1986).

Prenatal experience, rather than genetics or postnatal effects, has also been proposed as a specific cause of sagittal synostosis. It has been suggested that intrauterine compression may account for many congenital idiosyncratic occurrences (Thoma, 1907; Higgenbottom et al., 1980; Koskinen-Moffatt et al., 1982). Babies who descend into the maternal pelvis prematurely or for a prolonged period of time (i.e., 6 weeks or more prior to delivery) experience attenuated lateral construction and a much higher frequency of sagittal synostosis (Graham et al., 1979). Fetal head constraint might, therefore, explain the disproportionate occurrence of sagittal synostosis over other craniostenosis. Because the potential for lateral constriction increases during the last trimester as growth in weight exceeds that in length, fetal head constraint may also explain the disproportionate sex ratio. Graham et al. (1979) hypothesize that because males have larger heads even as fetuses, they might experience exaggerated lateral constriction, creating the higher frequency typically found in males. If cranial width is, in fact, a critical variable, one would also expect that normally brachycephalic populations, such as the Maya (Saul, 1972; Stewart, 1953), would experience higher rates of sagittal synostosis than nonbrachycephalic populations. However, good comparative populational data are not available to test this hypothesis.

Neither craniostenosis, in general, nor sagittal synostosis, in particular, have been statistically analyzed in skeletal populations. The association of any kind of synostosis with intentional cranial deformation has received little attention, in spite of a noted association between cranial base and vault deformities in both altered and normal skulls (Moss, 1958; McNeill and Newton, 1965; Anton, 1989). In the only study of purposefully deformed crania which focuses on synostosis, Bennett (1967) notes a high frequency (52.6%) of sagittal synostosis in a sample of 19 posteriorly deformed crania from a variety of sites from the prehistoric southwestern United States.

WORMIAN BONES

Sutural (wormian) bones are small ossicles of irregular size and shape located within fontanelles and the two borders of cranial sutures. They result from the presence of distinct ossification centers that may detach from the primary centers of larger associated cranial bones (Pendergrass et al., 1956). As separate bones, they usually extend from inner to outer tables of the cranial vault, but may involve only one table (Inkster, 1953). They occur mainly in the posterior and lateral vault (Ossenberg, 1970), and can vary in number per individual from none to over 100 (Hektoen, 1903; Armstrong, 1928). The population incidence of wormian bones is usually quite high (Brothwell,

1963), but appears to be variable between populations (Sullivan, 1922; Berry and Berry, 1967; Brothwell, 1972; Ossenberg, 1970).

The etiology of wormian bones has been attributed to both genetics and external forces. Wood-Jones (1931) regarded wormian bones as nonadaptive discontinuous traits useful in population distance studies. Their heritable nature was supported by Torgerson's (1954) pedigree research, which indicated that they were heritable traits with 50% penetrance and expression. Other research strongly suggests that the mechanisms responsible for the formation of wormian bones are not simply genetic. For example, their association with hydrocephalus (Hess, 1946; Richards and Anton, 1991) has led to two interpretations. Hess (1946) suggests that they are a hypostostic reaction to an inherited metabolic disorder of the mesoderm, but Anton et al. (1992) suggest that their occurrence in this context is a consequence of increased pressure on the sutures from internal expansion. Experimental work my Moss (1957) and Oudhof (1982) supports the role of external force (in the form of muscular action) on altering suture morphology. Anton et al. (1992) note that both wormian bones and sutural interdigitation are measures of sutural complexity which provide a means of inferring alterations in forces. This relationship has been used to reconstruct the intensity and direction of stress in animals whose activities place strong external forces on their skulls, e.g., reptiles (Gans, 1974), pigs and peccaries (Herring, 1972), and goats and sheep (Jaslow, 1989, 1990). Similarly, tensile and compressive forces have been inferred from sutural structure (Herring and Mucci, 1991). Sutural complexity, at least in the form of interdigitation, confers greater bending strength and ability to absorb energy (Jaslow, 1990), and can therefore be considered an adaptive response to external stress. The adaptive model has been used by many researchers who have associated wormian bones with artificial deformation (Dorsey, 1897; Dembo and Imbelloni, 1938; Bennett, 1965; Gottlieb, 1978). In experimental skull binding on rats, Puciarelli (1974) found that the deformed group formed significantly more wormian bones. He suggests the trait is an epigenetic polymorphism caused by "retardation in dermocranial ossification" resulting in accidental ossification centers which increase the probability of wormian bone formation. This model is clearly one of mechanical force superimposed on genetic predisposition, and has been argued in other studies of artificial deformation in humans (Ossenberg, 1970; El-Najjar and Dawson, 1977). Although, in the context of external force, the probability of wormian bone formation may be increased by genetics, Jaslow (1989) would argue that sutural morphology could be affected by force alone. Tensile forces are particularly implicated by experimental research on fibroblasts (Hickory and Nanda, 1987), and the observations of Anton et al. (1992) on artificially deformed crania of different types from Peru. However, the distribution of forces involved in cranial deformation is complex, as is the resultant patterning of sutural complexity. For example, Anton et al. (1992) find that more sutural bones occur in antero-posteriorly deformed skulls, but more interdigitation occurs in circumferentially deformed skulls. In Mesoamerican populations, wormian bones have received very little attention, in spite of the high frequency of cranial deformation reported.

MATERIALS AND METHODS

The study sample consists of 143 adult crania from the large Maya ceremonial center of Lamanai, in northern Belize. Located on the northwest shore of the New River Lagoon, Lamanai exhibits a continuous time sequence spanning the Preclassic (2500–1250 B.C.) to Historic (1520–1670 A.D.) periods. It was excavated by David Pendergast, Royal Ontario Museum, and the skeletal sample is curated in the Department of Anthropology at Trent University, Peterborough, Ontario. All of the observable material for this study comes from the Postclassic (1000–1520 A.D.) and Historic (1520–1641) periods. Of the observable sample (N = 143), 15 or 12% were undeterminable for deformation, and therefore were not used in the analysis. The sex ratio of the entire sample is almost equal, and this equality is main-

tained in both deformed (N = 46) and undeformed (N = 82) sets. Determination of sex can be confounded by artificial deformation (Ossenberg, 1970), as well as premature suture closure (Reichs, 1989). Therefore, an attempt was made to reduce error in age and sex determination by using as many postcranial and cranial traits as possible. Although deformation appears to be a gender-related practice at some sites (MacCurdy, 1923; Ossenberg, 1970), this does not appear to be the case at Lamanai. It is not possible to determine if deformation at Lamanai is status related, as most of the sample comes from ceremonial and elite structures, or from Christian churches with no differentiation in grave goods.

Preservation is poor, as it is at most tropical forest sites. Although Lamanai represents one of the largest Maya samples to date, the remains are mostly fragmentary. Therefore, a full set of observations on each skull and multivariate analysis were impossible. The majority of deformed skulls come from the Postclassic period (Table 1). Of these, 71% of the determinable sample were deformed. The large number of undeformed skulls is a consequence of excavation and preservation bias favoring the Historic period. Of the total of 128 crania with identifiable deformed or normal morphology, 72 were from the Historic period. Only six Historic crania were intentionally altered. The lower frequency of deformation in the Historic period is probably related to ideological and behavioral change created by the Spanish Christian intrusion on Maya society. Lamanai was, however, protected somewhat from intense Spanish cultural oppression because it was a *visita* site, i.e., the Spaniards were not likely permanent residents at the site. Control was maintained by periodic visits from friars. Pendergast has noted that the Spanish appear to have had little influence on the material culture at Lamanai, so it is interesting to find such a dramatic change in biocultural expression. The Historic period material is represented by two church "graveyards"; an earlier one (N/12-11) dating to roughly 1544 (Pendergast, 1985), and a later, more impressive structure (YDL) which was probably built near the end of the 16th century. Interestingly, there is a higher frequency of deformation in the more recent church (11% of the determinable sample compared with 4% in the earlier church). This pattern could be reflecting an ideological rebellion consistent with evidence of a revolt at the site, which ended the Spanish hegemony. The second church was burned and the inhabitants moved further inland to the site of Tipu, Belize.

The style of deformation practiced at Lamanai is a form of anteroposterior deformation which falls into the typical "tabular oblique" classification described by Imbelloni (1950). This style is also common to many other Maya lowland sites (Stewart, 1948, 1953; Romero, 1970), and is represented in the art found on stelae, ceramic vessels, and in figurines. It is characterized by flattening of the frontal and occipital bones, a bulge anterior to a depression along the axis of the coronal suture, lateral bulging of the parietals, and frequent depression along the sagittal suture, which together create a bilobal effect in superior or posterior views. Deformed cranial vaults are tightly compressed anteroposteriorly. Compensatory growth occurs laterally in both parietal and frontal regions. Previous analysis of anteroposterior deformation indicates that it creates a wider, shallower base, a wider vault and face, and a shorter face (Anton, 1989; Cheverud et al., 1992).

The method used by the Maya for creating this head form is described in an early ethnohistoric account by Friar Diego de Landa (1566, pp. 52–53).

> "Four or five days after the child was born they laid it on a cot made of rods face down, with the head between two pieces of wood, one on the occiput and the other on the forehead, tying them tightly, and leaving it suffering for several days until the head, thus squeezed, became permanently flattened as is their custom."

It is doubtful that a permanent deformation could have been completed in only "several days." Accounts in other cultures indicate a treatment period of up to a year or more (Dingwall, 1931). Although no deforming apparatuses have been preserved in the Maya region, there are pictorial descriptions of the apparatus described above from South America (Imbelloni, 1950). Such appa-

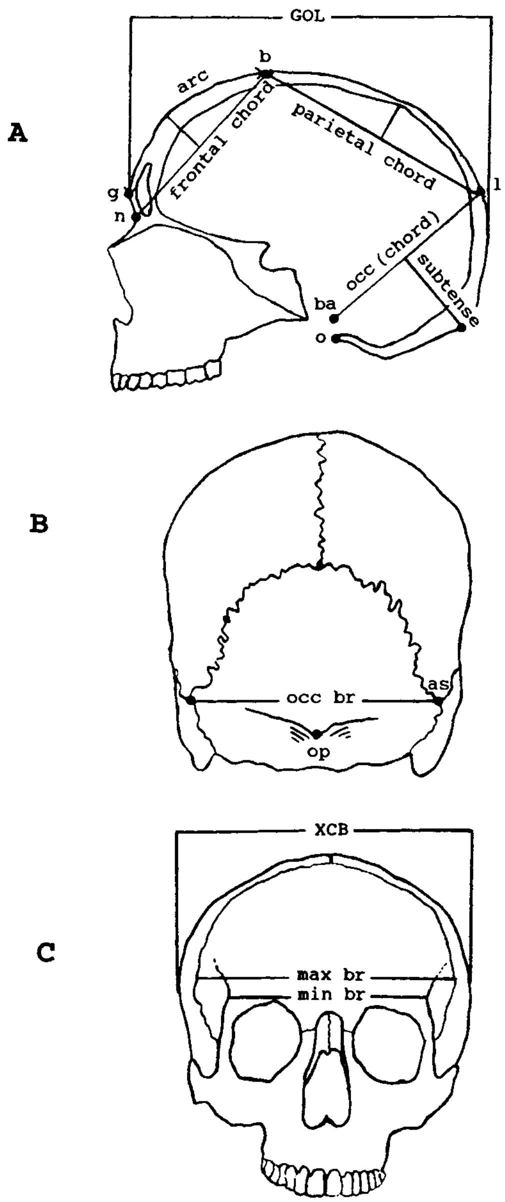

Fig. 1. Landmarks and measurements used in this study (after Bass, 1987; Howells, 1973). **A:** Medial aspect of hemisected skull (diagrammatic). **B:** Posterior view of skull. **C:** Frontal view. Abbreviations: n, nasion; as, asterion; b, bregma; ba, basion; g, glabella; GOL, glabello-occipital length; l, lambda; max br, maximum frontal breadth; min br, minimum frontal breadth; o, opisthion; occ br, occipital breadth; occ (chord), occipital chord; op, opisthocranion; XCB, maximum cranial breadth.

ratuses from South America have also been found in sets of graduated sizes, suggesting a continual refitting, as head size increased with age (Enrique Gerzsten, personal communication). The adult form of cranial alteration was observed in one 2-year-old, suggesting that the deformation was morphologically well defined by that age. Although these skulls exhibit the characteristic tabular oblique morphology, there is considerable variation in the degree of deformation.

Four deformed individuals are excluded from the sample. These include two congenital cases (oxycephaly and plagiocephaly), and two Historic skulls which exhibit a lambdoidal flattening only and are distinguished morphologically from the rest of the sample. Lambdoidal flattening is commonly found in the northern Yucatan (Hooton, 1940). Because Lamanai had developed a trade affinity with Yucatan sites in the Postclassic and Historic periods (Pendergast, 1985, 1986), it is possible that these two individuals were visitors from the north.

On the basis of consistency in deformation type and the assumption of biological continuity, Historic and Postclassic samples are pooled for analysis. Because of the fragmentary nature of the sample, all measurements are taken within single bones, with the exception of a few measures of maximum cranial breadth (XCB) and cranial length (GOL). All of the major vault bones for both normal and deformed skulls were measured for their arc, chord, subtense, and basic dimensions (after Bass, 1987, and Howells, 1973). Measurements were taken by the author using sliding and spreading calipers. Curvature indices were calculated from the arc–chord measurements to quantify a comparison of deformation effects on separate bones. The higher the index, the flatter the bone. The total number of individuals represented in the sample is not reflected in the measurement sets, as only three individuals could yield a full set of data. Measurements were taken from every bone that would provide at least one. Student's t tests performed on the data determined the significance of morphological change and its differential effects (Table 2).

Sagittal synostosis was scored as either

TABLE 1. *Representation of fronto-occipital cranial deformation by time period*

Time period	Deformed	Undeformed	Undeterminable
Postclassic	40	16	6
Historic (1st church)	1	27	0
Historic (2nd church)	5	39	9
	46	82	15

TABLE 2. *Metric data for deformed and undeformed crania at Lamanai*

	Deformed			Undeformed			
Measurement[1]	N	Mean	SD	N	Mean	SD	P[2]
Frontal							
Chord	14	100.5	12.1	22	106.1	7.5	0.139
Arc	8	102.6	6.4	21	117.4	5.8	0.0001***
Subtense	7	8.8	4.7	22	21.3	3.7	0.0001***
Curv. index	5	94.6	2.5	21	87.3	3.4	0.004**
Min. br.	8	111.1	19.4	12	92.8	2.5	0.004**
Max. br.	6	126.5	7.1	13	114.4	6.4	0.002**
Parietal							
Chord	7	97.1	6.9	22	105.7	5.7	0.003**
Arc	5	109.4	7.0	20	121.3	8.5	0.009**
Subtense	7	18.2	2.8	21	23.9	3.4	0.0001***
Curv. index	5	91.4	2.4	20	87.9	3.3	0.035*
XCB	5	173.6	23.0	16	146.5	14.3	0.005**
Occipital							
Chord	5	87.4	8.0	15	92.7	6.4	0.151
Arc	3	97.3	7.4	14	111.1	7.4	0.011*
Subtense	5	19.2	3.7	15	24.9	3.4	0.006**
Curv. index	3	84.6	1.0	14	83.6	2.5	0.495
Ht/br index	4	114.1	26.2	11	81.6	6.3	0.206
Biaster. br.	8	100.0	41.7	23	111.2	5.7	0.205
La-op	8	52.4	8.2	15	52.8	20.9	0.968
Op-o	4	50.3	5.4	9	28.7	17.4	0.036*
GOL	4	155.3	9.4	14	168.5	5.1	0.002**

[1] Abbreviations: GOL, glabello-occipital length; XCB, maximum cranial breadth; la, lambda; op, opisthocranion; o, opisthion; curvature index, chord/arc × 100; ht/br index, biasterionic breadth/height × 100.
[2] Asterisk indicates statistical significance.

present or absent. The lack of reliability in determining age at death from the timing of cranial suture closures begs the question of premature closure (Meindl and Lovejoy, 1985; Key and Aeillo, 1994). In this study, premature sagittal synostosis is identified by a marked differential fusion between the sagittal suture and the other major vault sutures (i.e., the sagittal suture must be obliterated both endocranially and ectocranially when the other sutures are still open). The presence of premature sagittal synostosis was determinable in only 76% (n = 97) of the observable sample. Some observation error may have been created by the fragmentary nature of the sample, which did not always allow assessment of all the other major sutures. However, such errors should be systematic for both deformed and undeformed individuals.

To compare the morphological effects of synostosis on both deformed and undeformed skulls, length and breadth measurements were taken wherever possible, and divided into categories of deformed and undeformed crania, with and without sagittal synostosis (Table 3). Cranial indices were calculated from these measures to demonstrate differences in form: i.e., an index less than 100 illustrates a skull that is longer than it is broad; over 100, vice versa. The possible association between synostosis and deformation was tested using a contingency χ^2 (Table 4).

In the analysis of wormian bones, the sample was selected and pooled as it was for sagittal synostosis. Only ossicles over 4–5 mm in diameter were considered. Observation was limited to ossicles in the lambdoid suture between asterion points, as this was

TABLE 3. Comparison of basic length and breadth dimensions for deformed and undeformed crania, with and without sagittal synostosis

	Cranial le. (GOL)			Cranial br. (XCB)			Cranial index[1] (CI)
	N	Mean	sd	N	Mean	sd	
Undef/normal sutures	10	170.1	4.3	12	145.3	9.2	85.4
Undef/sagittal syn.	4	174.5	9.5	2	145.5	2.1	83.3
Def/normal sutures	3	160.3	9.8	3	167.5	5.5	104.5
Def/sagittal syn.	3	151.7	13.3	3	185.7	28.0	122.4

[1] Cranial index, breadth/length × 100. An index of less than 100 means that length exceeds breadth; an index of more than 100 means that breadth exceeds length.

TABLE 4. Data used for testing the association between deformity and sagittal synostosis

	Synostosis	Normal	Total
Deformed	15	22	37
Undeformed	3	69	72
Total	18	91	109

TABLE 5. Data used for testing the association between wormian bones and artificial deformation

	Wormian bones	No wormian bones	Total
Deformed	14	2	16
Undeformed	23	27	50
	37	31	66

the section most commonly preserved. However, only 45% of the crania were observable for this trait, fewer than for sagittal synostosis. Preservation also precluded a valid quantification of the number of ossicles present in this area per individual, so wormian bones were simply scored as either present or absent. Ideally, a complementary analysis of interdigitation would have provided interesting comparisons with other work that attempts to differentiate the nature of force via its sutural effects (Herring and Mucci, 1991; Anton et al., 1992), but the sample is not well enough preserved for taking commensurate data. The association between the presence of wormian bones and deformation was tested using a contingency χ^2 (Table 5).

RESULTS AND DISCUSSION

Metric analysis confirms that deformed skulls are significantly shorter and broader than undeformed skulls (Table 2). Of the vault bones, only the parietals are significantly altered in length,and thus must account for most of the anteroposterior compression. The parietals are the only major vault bones that are not directly articulated to the base or face, and their development is the least complex. Their development under normal conditions is controlled by growth under internal pressure of the expanding brain mass, and by sutural growth at frontal, temporal, and occipital margins (Enlow, 1968, 1990). Breadth measures indicate that, under anteroposterior deformation forces, compensatory growth occurs laterally, mainly in the frontal and parietal areas. Occipital breadth is not significantly affected. These morphological measures support the previous findings of other researchers (Helmuth, 1970; Anton, 1989; Cheverud et al., 1992).

The arc and subtense measures and curvature indices indicate that all of the curvatures along the sagittal plane are flattened anteroposteriorly. The greatest degree of flattening occurs in the frontal and the least in the occipital. The stability of the occipital is thus consistent in this measure as well.

Premature sagittal synostosis is found in both deformed and undeformed skulls in this sample, and might have more than one cause. Sagittal synostosis occurs in 3% of the undeformed sample, and unless the identification of both deformation and synostosis is in extreme error, this is much higher than the incidence of 0.04% for modern live births (Graham et al., 1979). If fetal head constraint can be considered a cause, the unusually high incidence in the undeformed sample could suggest a predisposition caused by the natural brachycephalic morphology of the Maya. The undeformed sample from La-

manai with no sagittal synostosis has a cranial index of 85.4 (Table 3), which would be characterized by Bass (1987) as hyperbrachycephalic. The association of brachycephaly with sagittal synostosis is, however, only a hypothesis. A more comprehensive comparison of population data would be a useful test of the fetal constraint hypothesis.

Virtually all of the pre-Historic crania have purposefully altered morphology and 31% of the pre-Historic sample exhibit premature sagittal synostosis, compared to 16.5% for the total sample. Most of these cases (41%) are accounted for by artificial deformation. In testing the association between deformation and sagittal synostosis, a χ^2 (contingency) on the pooled sample indicates that the pathology is highly dependent on fronto-occipital alteration ($P < 0.0001$, df = 1, N = 109; Table 4). These results are not unlike those found by Bennett (1976) in skulls with posterior deformation only.

In Bennett's sample, and in otherwise undeformed skulls, premature sagittal synostosis normally leads to a bulging along the sagittal suture line (scaphocephaly), lengthening of the skull (dolichocephaly), and cessation of lateral growth in the parietals. In the undeformed sample with sagittal synostosis from Lamanai, those with sagittal synostosis do appear to have elongated skulls (Table 3). The same sample yielded only two breadth measures, which are not different from the undeformed sample with normal sutures.

The characteristic morphology resulting from premature sagittal synostosis is reversed in deformed crania with sagittal synostosis (Table 3). Although the sample is small (n = 3), these individuals have the shortest and broadest crania. In addition, there appears to be a depression along the line of the sagittal suture, and the extreme lateral growth in the parietals creates two distinct superior domes in a bilobal effect. Although it is questionable that the morphological effects of modification can be differentiated from those of synostosis based on these data, it appears that sagittal synostosis in combination with fronto-occipital deformation exaggerates the shortening and broadening effects previously observed (Anton, 1989; Cheverud et al., 1992).

Two possible explanations might be offered for the synostosis. One relates to alterations in basicranial morphology, and the other to mechanically induced constraint or tension. Pathological suture fusion is associated with cranial base alteration in modern populations (Moss, 1959; Burdi et al., 1986). Basicranial development is usually affected by abnormalities in vault morphology because of the restricted development and redirected growth of functionally and morphologically related vault bones (McGibbon, 1865; Oetteking, 1924, 1930; Moss, 1958, 1959; McNeill and Newton, 1965; Anton, 1989; Cheverud et al., 1992). Premature synostosis in all of the major vault joints has been observed in association with a deformed base. Moss (1960b) theorizes that the dura mater and falx cerebri transmit tensile messages from the base to vault sutures, thereby regulating sutural growth. From five sites on the base—the crista galli, the lesser wings of the sphenoid, and the petrous crests of the temporal bone—the dura mater attaches with fiber systems which determine the direction of neurocranial growth and, consequently, the ultimate morphology of the brain. Association with these dural fiber systems are fibrous septa which appear very early in life and extend from the dura mater into the cranial cavity. Moss (1959; Moss and Young, 1960) has suggested that changes in the position of the points of attachment for the dura mater (particularly the cribriform plate and the crista galli) prevent the neurocranial capsule from responding normally to the forces of the growing brain, and that dural change predisposes to pathological suture fusion. Although the relationship between base alteration and synostosis has been recognized, Folz and Loeser (1975) note that the question of causal relationships is yet unresolved.

The external measures of the occipital in the deformed sample are the least affected of all the major vault bones (Table 2). Although not all of the occipital measures are restricted to base measures, all but one (biasterionic breadth) include some portion of the base. This finding is consistent with the relative stability of the cranial base observed by medical researchers in nondeformational conditions (Björk, 1955; Moss and

Greenberg, 1955; Young, 1960; Anderson and Popovich, 1983). Nonetheless, endocranial base change might have been much more significant. Only one deformed skull in the Lamanai sample had a base preserved. As this is not a sufficient number to establish a range of variation in base deformities described by Moss (1958) and McNeill and Newton (1965), base morphology cannot be compared with validity here.

Some measurements, however, suggest the possibility that purposefully deformed skulls had deformed bases. The distance between opisthocranion and opisthion was significantly greater in deformed skulls (Table 2). Thus, there might be a deformation of at least some of the attachment areas of the falx cerebri, which could contribute to premature fusion of the sagittal suture. In his series of deformed skulls, Bennett (1969) emphasizes the role of the falx cerebri in creating premature fusion of the sagittal suture because it directly underlies the sagittal suture area, creating tension. Although Moss has theorized the importance of tension, and this theory is reinforced by experimental work on animals (Babler et al., 1982), the question of base–suture relationships becomes confounded in a chicken-and-egg fashion. In terms of tension vs. base deformation, it is not valid to argue the dominance of one over the other for this sample. However, as both theories involved tension at some level, the sample can be used to address the role of tensile forces in creating sutural anomalies. There are also two more proximate issues: why only the sagittal suture, and what causes the tension?

The association of sagittal synostosis with intrauterine compression leads us to question the relative roles of constraint vs. tension. Although empirical evidence indicates that compressive force can fuse the sagittal suture prenatally (i.e., third trimester) (Thoma 1907; Graham et al., 1979; Higginbottom et al., 1980), experimental evidence demonstrates that sutures will not fuse as a result of postnatal compression (Moss, 1957). Koskinen-Moffatt et al. (1982) suggest that after birth sutures become more vascularized, differentiated, and capable of repair and regeneration, which may inhibit fusion under compressive forces. Normal development of the growing brain produces a general state of tension on sutures. Relative growth rates of vault bones and mechanical factors involved in fiber orientation are known to be important in suture growth and fusion (Van Limborgh, 1972; Smith and McKeown, 1974; Babler et al., 1982; Oudhof, 1982). Tensile forces on sutural tissues produce an adaptive growth response at the suture (Babler et al., 1982; Enlow, 1990). Under tensile stress, normal osteogenesis and fibrillogenesis are followed by bone remodeling, leading to synostosis (Ten Cate et al., 1977). In vivo research on the mid-sagittal suture of rats indicates that tension increases the release of fibroblasts or fibroblast precursors in the DNA synthesis phase (Hickory and Nanda, 1987). Although the fusion response of sutures to tension has been described by others (Hinrichson and Storey, 1968; Jackson et al.,1979), Hickory and Nanda (1987) note that the fusion reaction to tension is mitigated by the magnitude and control of force. For example, experimental evidence suggests that too much tension can actually inhibit fusion (Hickory and Nanda, 1987). A perinatal restraining device for fronto-occipital deformation could alter the normal tensile forces created by the growing brain, producing localized areas of compression and tension along sutures in varying degrees of force (Anton et al., 1992). Localized tension along the sagittal suture during a critical period of normal growth could explain the occurrence of sagittal synostosis in artificially deformed skulls. Variability in response observed from deformed skulls could be attributed to differences in magnitude and control of force, differences in growth activity between coronal, sagittal, and lambdoidal sutures, and differences in the deforming forces themselves.

Of all the major sutures, the sagittal suture might experience the optimal amount of tension under conditions of deformation. The majority of growth in the sagittal suture occurs earlier than in most other major vault sutures—i.e., from fetal life to age three—compared with growth in the coronal and lambdoidal sutures, which takes place from age three to 10 (Young, 1957). If a device restraining both frontal and occipital bones was in place shortly after birth, as the ethno-

graphic account indicates, and maintained at length, the suture most susceptible to premature closure should indeed be the sagittal. The phenomenon of compensatory bulging and lateral growth is probably due to relatively equalized anteroposterior compressive forces, as opposed to the unidirectional force in posterior deformation and the lengthwise narrowing in the skulls documented by Bennett (1967).

The analysis of wormian bones has a further potential to contribute to our understanding of force alteration. Among the normally formed skulls, the frequency of wormian bones is almost 46%. Such a frequency could be consistent with Torgerson's (1954) definition of wormian bones as a dominant heritable trait with 50% penetrance. However, the formation of wormian bones also seems to be highly dependent on artificial deformation (contingency χ^2) ($P < 0.017$, df = 1, N = 66; Table 5). Only two (12%) of the 16 deformed crania did not exhibit wormian bones. Thus these data support the genetic cum environment model indicated by clinical experiment (Moss, 1969; Van Limborgh, 1970; Puciarelli, 1974; Markens and Oudhof, 1980; Oudhof, 1982) and in observations of artificially deformed crania (Ossenberg, 1970; Gottlieb, 1978). The style of deformation also appears to create different responses in the manifestation of wormian bones. As different styles represent different configurations of force, this is not surprising. For example, Anton et al. (1992) found more absolute numbers of sutural bones in cases of anteroposterior deformation, but more individuals with sutural bones in circumferential deformation. Because the quality of the Lamanai sample would not allow scoring in absolute numbers relative to simple presence or absence, it is unclear whether these data support the findings of Anton et al.

Although there does seem to be a relationship between force and the formation of wormian bones, the nature of the force is unclear. Tension has been cited as a causative factor (Anton, 1989; Anton et al., 1992). However, the timing and degree of force relative to the periods of maximum growth for the major vault sutures can be expected to produce variability in response. For example, wormian bones are not observed in the sagittal suture for this sample, yet the presence of tensile forces is implicated by premature suture fusion. The response to altered force in the occipital appears to have been the formation of ossicles. The different response could be related to a number of factors. The period of maximum growth in the lambdoidal suture—i.e., 3–10 years of age (Young, 1957)—is later than that of the frontal. The force exerted by deforming apparatuses is expected to be most intense prior to the onset of growth in the lambdoidal suture. As the case of the 2-year-old Lamanai child previously mentioned suggests, most of the deformation could have been complete by age three. It is still possible that the lambdoidal suture was subject to tensile force from the deforming apparatus, and that the formation of ossicles, like the interdigitation found in Jaslow's (1989) head-butting sheep, increased the bending strength of that part of the cranium butted against a deforming apparatus. Unlike Jaslow's sheep, or any of the other animals whose activities appear to create different sutural morphology, the use of a deforming apparatus was not likely habitual over a lifetime, but temporally circumscribed in the early years. Alternately or additionally, the normal growth vectors in the occipital area of the older child might have been sufficiently altered by deformation to create sutural anomalies such as ossicles and interdigitation. The morphological response to abnormal tension in sutural tissues seems to vary from fusion to ossicle formation to interdigitation, depending on the amount of force and the timing of its application. Both sagittal synostosis and wormian bones can be viewed as adaptive responses to abnormal forces. Although the external application of force involved in deformation is the primary cause for altered force, the resultant changes in bone-to-bone relationships and probably also in the cranial base would create, in themselves, sources of altered force. We can infer the presence of altered tensile forces from an examination of sutural responses, but we still need to know more about what creates the differences in responses.

CONCLUSIONS

Intentional fronto-occipital cranial alteration among an ancient Maya population

has been used as a retrospective illustration of some of the growth principles and processes in cranial vault sutures. Metric analysis indicates that the deformed crania are significantly shorter and broader than undeformed crania, and that this effect may be further exaggerated by sagittal synostosis. Dimensionally, the parietal area is most strongly affected by this type of deformation, and the occipital is the most stable. The undeformed Maya at Lamanai might exhibit a much higher frequency of premature sagittal synostosis than usual because their hyperbrachycephalic head form could predispose them to stronger lateral constriction forces in utero and a higher congenital incidence. This hypothesis requires further testing.

The strong association of sagittal synostosis and wormian bones with fronto-occipital deformation demonstrates the importance of altered forces in sutural development and the developmental interdependence of cranial components. Although tension cannot be considered a more important cause for sagittal synostosis than cranial base deformation, in the context of Maya anteroposterior deformation it appears that tensile forces play a significant role in creating both sagittal synostosis and wormian bones. It is suggested that differential forces are set up by the deforming apparatus at critical periods for growth and development. The parietals may have been subjected to the most extreme tensile forces during their peak period of normal growth. The sutural response is likely an adaptive one which accounts for the synostosis. The association of wormian bones with deformation allows the inference of altered force in the occipital bone as well. The conditions and timing of growth in the occipital are markedly different than those in the parietal, which may account for the difference in sutural response.

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